Doklady Earth Sciences, Vol. 393. No. 8, 2003, pp. 1093-1097. Translated from Doklady Akademii Nauk. Vol. 393. No. 1. 2003, pp. 83-87.

========================== GEOLOGY ============================

Pb-Pb Isochron Age and Sr-Isotopic Signature of the Upper Yudoma Carbonate Sediments (Vendian of the Yudoma-Maya Trough, Eastern Siberia)

Academician of the RAS M. A. Semikhatov[1], G. V. Ovchinnikova[2], I. M. Gorokhov[2], A. B. Kuznetsov[2], O. K. Kaurova[2], and P. Yu. Petrov[1]

Receivcd July 10, 2003

The Yudoma Group of the Uchur-Maya region is one of the well-known and widespread Upper Precambrian lithostratigraphic units in Siberia. This group completes the Upper Precambrian section in both paleostructures (Uchur-Maya Plate and Yudoma-Maya Trough) divided by the Nel'kan Thrust Fault [I]. The Yudoma Group unconformably overlies different-aged older rocks varying from pre-Riphean basement of the Siberian Platform to ultramafic intrusions emplaced into all Riphean sequences. The base *(N. sunnaginicus* Zone) of the Variegated Formation of the Tommotian Stage (Lower Cambrian) [1-3] makes up the upper boundary preceded by a regional erosion (locally, a minor angular unconformity). Owing to the structural autonomy and specific paleontological characteristics of the Yudoma Group, it was referred to as a type of chronostratigraphic unit (Yudoma Complex or Yudomian) [I, 2, 4] equivalent to the Vendian in the East European Platform. Although this viewpoint is widely accepted and fixed in the Precambrian stratigraphic scale of Russia in 1990, it cannot be regarded as a rigorously substantiated unit, because the available paleontological data do not prove the synchronism of Yudomian and Vendian boundaries and reliable isotopic dates of the Yudoma Group are lacking.

The available U-Pb age values for pre-Yudomian ultrabasic intrusions are sharply discordant. They were obtained for different minerals with a high content of common Pb and interpreted by the same authors in different works as values defining the age of intrusive rocks ranging from 600 ± 100 to 650 ± 40 Ma [I, 5], The K-Ar isotope systems of biotite from the outer contact of intrusions and phlogopite from associated carbonatites are obviously disturbed, as indicated by a wide scatter of age estimates from 586 to 740 Ma [5].

[1] *Geological Institute, Russian Academy of Sciences, Pyzhevskii per.* **7,** *Moscow, 119017 Russia; e-mail: semikhatov@ginras.ru*

[2] *Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, nab. Makarova 2, St. Petersburg, 199034 Russia*

The same is true of mineralogically unspecified glauconites from the Yudoma Group and the Variegated Formation base. The K-Ar age obtained for glauconites by G.A. Kazakov and K.G. Knorre varies from 560-660 to 510-610 Ma, respectively [I, 5]. Moreover, there are some grounds to assume that the material used for the age determinations contained an admixture of allogenic K-bearing minerals, because the mineral fractions of Al-glauconite from the Variegated Formation base have a K-Ar age of 459-476 Ma [6], The Rb-Sr errorchron value of 639 ± 30 Ma obtained by A.A. Krasnobaev, Yu.L. Ronkin, and O.P. Lepikhina for the fine (<1 μm) clay fraction of the Upper Yudomian (according to the modem data) mudstone [5] also does not solve the problem, because such fractions commonly include different-aged clay minerals and retain the isotopic memory on various lithogenetic events. The attempt to invoke U-Pb data on a few volcanogenic zircon grains in comparable sediments from the northern Siberian Platform [7] to constrain the age of Yudoma Group encounters difficulties related to the equivocal correlation of sections and the sometimes different interpretations of the stratigraphic position of the dated volcanic rocks [3].

Taking into account the aforesaid, we applied an approach based on the joint study of U-Pb and Rb-Sr systematics of the same samples taken from carbonate rocks of the upper Ust'-Yudoma Formation of the Yudoma Group. This approach allows us to select the least altered samples for Pb-Pb dating and, thus, obtain more reliable results. We can also get additional chemostratigraphic data on the age of the studied sequence if the $^{87}Sr/^{86}Sr$ ratio variation gradient is sufficiently high during the sequence accumulation (as, for example, in Vendian). We chose the Ust'-Yudoma Formation as a subject of research, because in contrast to the lower Aim Formation, this formation contains the characteristic fauna as an additional criterion for estimating the reliability of obtained isotopic values.

The larger (upper) part of the Ust'-Yudoma Formation in the Uchur-Maya Plate contains small shelly fossils of *A. trisulcatus* and *P. antiqua* zones pertaining to the terminal Nemakit-Daldynian Stage of the Vendian. In

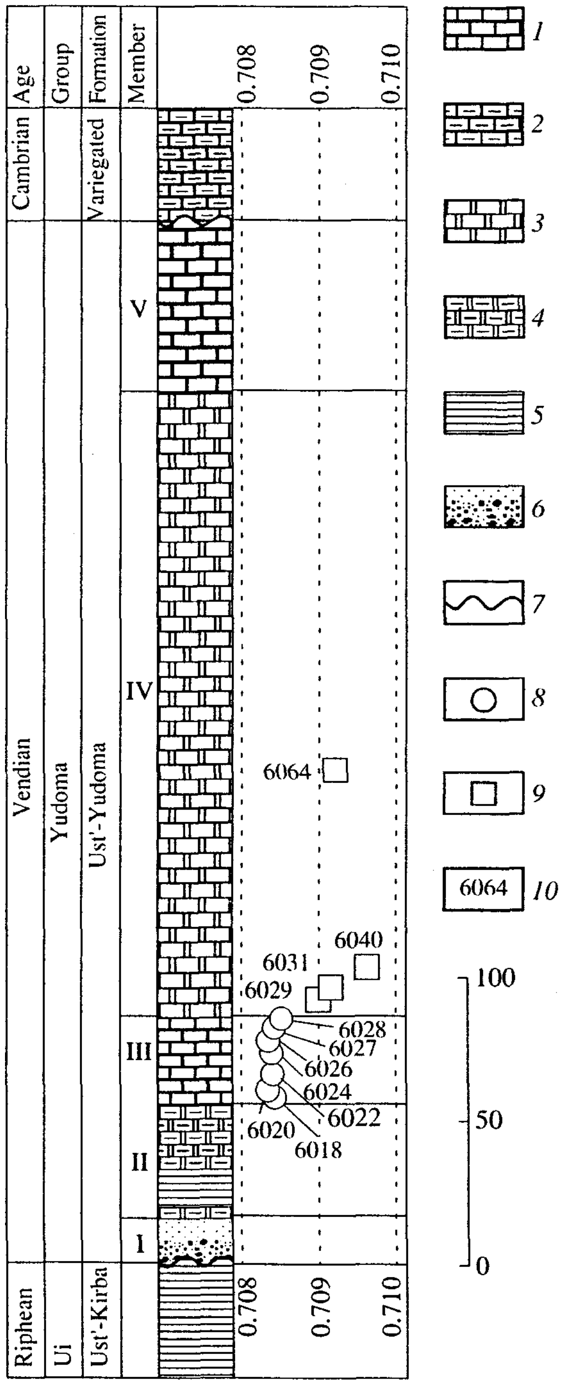

Fig. I. Stratigraphic column of the Ust'-Yudoma Formation, location of the samples, and their $^{87}Sr/^{86}Sr$ ratio. (*1*) Limestone; (*2*) clayey limestone; (*3*) dolomite; (*4*) clayey dolomite; (*5*) mudstone; (*6*) silty sandstone; (*7*) stratigraphic unconformity; (*8*) limestone; (*9*) dolomite; (*10*) sample number.

addition to the endemic *Suvorovella* and *Majaella* of ambiguous biological affinity, rare Ediacarian soft-bodied Metazoa *Medusinites* and *Cyclomedusa* ex gr. *plana* are contained in the smaller (lower) part of the formation [2], The *Medusinites* have a wide range of vertical distribution in beds with the Ediacarian fauna (M.A. Fedonkin, pers. commun.), whereas the typical *Cyclomedusa plana* occurs only in the upper beds overlying the tuffaceous zircon-bearing unit (U-Pb age 555.3 ± 0.3 Ma) in the Belomorian sections [9]. The determination of the Yudomian form as C. ex gr. *plana* naturally diminishes the stratigraphic significance of this finding.

In the studied section of the Ust'-Yudoma Formation along the Yudoma River near the Ulakhan-Yatygy River mouth, this formation cuts the Aim Formation and unconformably overlies mudstones of the Upper Riphean Ust'-Kirba Formation. The 16-m-thick basal sandstones and gritstones of the Ust'-Yudoma Formation (Member I) are overlain by a thick (340-370 m) succession of four carbonate beds (members II-V), which are, in turn, unconformably overlain by fossiliferous sedimentary rocks of the lowerTommotian Stage [I]. Member II (38-40 m) is composed of variegated (gray in the upper part) low-Mg (Mg/Ca = 0.421-0.607) dolosparites and dolomicrites with a substantial admixture of clayey and silty-sandy materials (5.6-13%) and interlayers of carbonate mudstone. Silicified dolomicrite layers and fine-grained pyrite dissemination (<3 mm) are noted in the upper 22-23 m of the section. The dolomites are characterized by high contents of Mn (160-340 ppm) and especially Fe (2200-8240 ppm) probably due to the removal of these elements from the silisiclastic constituents of the rock and/or the supply from underlying sandstones. Member III (30 m) consists of black bituminous (C_{org} up to 0.02%) micrites (Mg/Ca = 0.002-0.017). The micrites reveal horizontal or low-angle cross-bedding and includes thin interlayers of clayey limestone, oncolite segregations, and irregular flakestone near the roof. The Mn and Fe contents in the carbonate fraction of limestones are low (27-65 and 640-1195 ppm, respectively) and correlate with the carbonate-free admixture (4.4-9.5%) composed of quartz, clay minerals, and kerogene film fragments. Member IV (200-220 m) consists of the light gray Iow-Mg dolosparite (Mg/Ca = 0.560-0.596) in the lower section (35-40 m) and grades upsection into the coarse-crystalline sugarlike dolomite (Mg/Ca = 0.577-0.605). The latter rock contains abundant crevices apparently related to the dissolution of gypsum crystals. The rare stromatolite layers and shrinkage cracks are noted in the upper part of the section. Member V (60-65 m) consists of dolomitized limestones (Mg/Ca = 0.014—0.090) with remains of the Nemakit-Daldynian *Anabarites trisulcatus.* The rocks of members IV and V are distinguished by a low siliciclastic admixture (0.3-3.2%) and low contents of Mn (60-200 ppm) and Fe (280-1310 ppm), increasing to 930 and 2490 ppm, respectively, only in the upper part of Member V.

A pilot collection of limestones from Member III and Iow-Mg dolomites from the lower part of Member IV was taken for isotopic studies. The sediments of Member III were deposited in a moderately deep-water subtidal environment during a highstand of sea, Rb–Sr and U–Pb characteristics of soluble carbonate fractions of limestones and dolomites from the Ust'-Yudoma Formation

Sample no.	Sampling level, m	Rock	Carbonate fraction	Rb, µg/g	Sr, µg/g	$\frac{^{87}Rb}{^{86}Sr}$	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{meas}$	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{init}$ (t = 550 Ma)	Pb, µg/g	U, µg/g	$\frac{^{238}U}{^{204}Pb}$	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$
6064	170	D	L1	0.12	23.4	0.0149	0.70975	0.70963	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
			L2–L6	0.13	70.2	0.0055	0.70922	0.70918	"	"	"	"	"	"
6040	100	D	L1	0.03	11.8	0.0079	0.71076	0.71070	"	"	"	"	"	"
			L2–L6	0.11	72.6	0.0042	0.70965	0.70962	"	"	"	"	"	"
6031	92	D	L2–L6	0.52	68.5	0.0221	0.70930	0.70898	"	"	"	"	"	"
6029	88	D	L2–L6	1.80	66.4	0.0794	0.70960	0.70913	"	"	"	"	"	"
6028	85	L	L1	11.2	1060	0.0309	0.70863	0.70839	"	"	"	"	"	"
			L2–L6	0.56	903	0.0018	0.70845	0.70844	1.26	2.53	146	27.715	16.133	38.427
6027	82	L	L2–L3	n.a.	n.a.	n.a.	n.a.	n.a.	0.27	n.a.	n.a.	53.494	17.662	40.300
			L4–L6	"	"	"	"	"	1.54	"	"	41.648	16.981	39.705
			L2–L6*	0.63	1190	0.0016	0.70843	0.70842	1.04	3.01	244	40.571	16.905	36.905
6026	77	L	L1	4.22	1710	0.0072	0.70845	0.70839	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
			L2–L6	0.57	1660	0.0010	0.70833	0.70832	0.64	1.23	149	32.166	16.413	39.407
6024	71	L	L2–L6	0.40	1490	0.0008	0.70838	0.70837	2.12	0.83	26.4	21.573	15.788	40.174
6022	64	L	L1	0.51	2090	0.0007	0.70846	0.70845	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
			L2–L6	0.15	1950	0.0002	0.70838	0.70838	5.02	1.46	18.8	19.925	15.709	38.360
6020	58	L	L2–L6	0.31	1290	0.0007	0.70830	0.70829	7.66	0.79	6.65	19.319	15.661	38.597
6018	56	L	L1	1.90	1380	0.0040	0.70842	0.70839	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
			L2–L6	0.10	1420	0.0002	0.70841	0.70841	5.35	1.53	18.5	19.842	15.690	38.199

Notes: Rocks: (D) dolomite, (L) limestone; fractions: (L1) carbonate fraction obtained by a single treatment of the sample with 0.5N HBr solution; (L2–L3) composite carbonate fractions obtained at the second and third steps of treatment; (L4–L6) composite carbonate fractions of the fourth, fifth, and sixth steps; (n.a.) not analyzed; (*) results of independent treatment of the sample by a leaching agent.

whereas Member IV was formed during the gradual shallowing of the basin and onset of its evaporation. Eleven samples (seven limestones and four dolomites) were chosen for the investigation of U–Pb and Rb–Sr systematics. The rocks are visually most homogeneous, devoid of fractures, localized far from terrigenous members, and distinguished by low Mn, Fe, and siliciclastic admixture contents. The samples were studied with the technique of stepwise dissolution. The advantages of this procedure focused on enrichment of samples in the primary carbonate material have been demonstrated previously in the study of Riphean carbonate rocks (see, for example, [8]).

The weighed sample was treated with 0.1N HBr at room temperature. The solution of this step was denoted as fraction L1. The residue was consecutively treated with five portions of 0.5N HBr up to the complete dissolution of the carbonate fraction, and the obtained solution fractions were denoted as L2–L6. The Rb–Sr systematics of all samples was studied in fraction L1 and composite fraction L2–L6. When studying the U–Pb systematics of Sample 6027, we analyzed composite fractions L2–L3, L4–L6, and L2–L6 (parallel run). Only fractions L2–L6 were investigated in other samples (table). Details of chemical separation and isotopic analysis of Rb, Sr, U, and Pb are described in [8, 10]. In the calculation of Pb–Pb isochron parameters, the uncertainties of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios (reproducibility) were accepted as ~0.10 and ~0.15%, respectively. The average $^{87}Sr/^{86}Sr$ value in the NIST SRM-987 standard during the data gathering was 0.71025 ± 0.00001 ($2\sigma_{av}$, $n = 3$).

Limestones from Member III contain 950–1960 ppm Sr, probably suggesting the presence of aragonite in the primary carbonate sediment. As the overlying Member IV is approached, the Sr content decreases. The low Mn/Sr (0.02–0.05) and Fe/Sr (0.35–0.80) ratios in limestones of Member III testify to the good preservation of these rocks and their suitability for both U–Pb dating and estimation of Sr isotopic composition in the sedimentation environment. On the contrary, high cavernosity, geochemical characteristics, and lack of primary sedimentary structures in dolomites from Member IV (Sr 66.4–70.9 ppm, Mn/Sr =

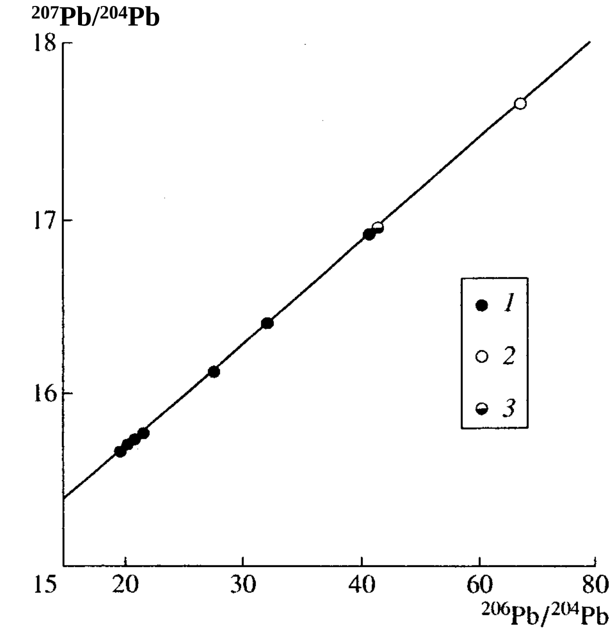

Fig. 2. The $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ plot for limestones of the Ust'-Yudoma Formation. (*1*) Fractions L1–L6; (*2*) fraction L2–L3, Sample 6027; (*3*) fraction L4–L6, Sample 6027. $t = 553 \pm 23$ Ma; MSWD = 0.8.

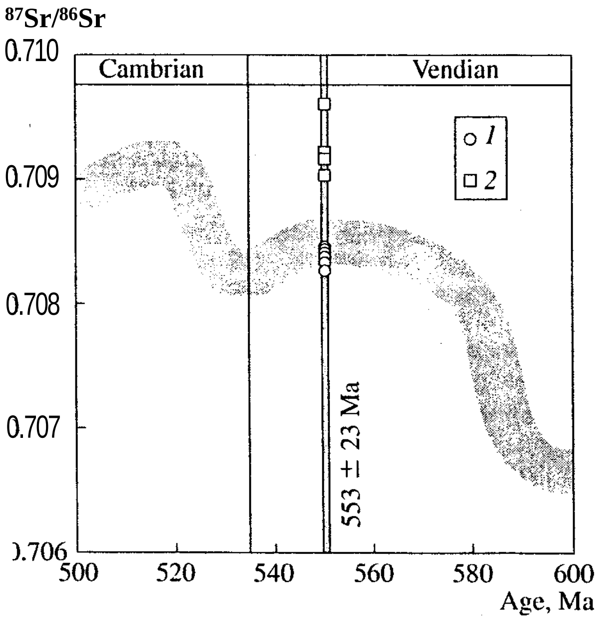

Fig. 3. The $^{87}Sr/^{86}Sr$ values in carbonate rocks of the Ust'-Yudoma Formation and the variation curve of the $^{87}Sr/^{86}Sr$ ratio in the Vendian and Early Cambrian seawater [11]. (*1*) Limestone; (*2*) dolomite.

0.85-1.30, Fe/Sr = 4.0-13.4) indicate an intense recrystallization of these rocks with the participation of meteoric fluid, probably during the pre-Cambrian hiatus. It is evident that the dolomites are unsuitable for U-Pb dating and the $^{87}Sr/^{86}Sr$ ratios (0.70922-0.70965) measured therein cannot serve as a basis for the Sr-isotopic characterization of the Yudomian seawater.

Fraction LI, which represents surface layers of carbonate grains, accounts for 4.2-4.9% in limestones of Member III and 2.2-2.8% in dolomites of Member IV. In the limestones, this fraction is more than 10 times more enriched in Rb relative to the subsequent composite fractions L2-L6 but is close to the composite fractions in Sr content (table). In the dolomites, fraction LI contains as much Rb as the subsequent fractions but is 4.5 times (on the average) more depleted in Sr relative to the subsequent fractions. The measured $^{87}Sr/^{86}Sr$ ratio in fraction LI of the limestones is slightly higher relative to the composite fractions L2-L6 (<0.0002). This difference reaches 0.0005-0.0011 in dolomites. It is evident that the removal of fraction LI releases limestone and dolomite samples from the secondary carbonates and enriches the subsequent fractions in the primary carbonate material.

Data points of these subsequent fractions of all analyzed samples lie on a straight line in $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plots. Because the data points of the studied fractions do not reveal a linear relationship in $^{208}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ - $1/^{204}Pb$ plots, the straight line in Fig. 2 is not a mixing line and has a geochronological sense. The age estimate based on nine points is 553 ± 23 Ma (2σ), MSWD = 0.8. By analogy with the previously studied carbonate rocks (see, for example, [8]), this value should be interpreted as a timing of the early diagenesis of carbonate sediments of the Ust'-Yudoma Formation. Thus, we have obtained the first stratigraphically significant Pb-Pb isochron date for Vendian carbonate rocks. Taking into account the stratigraphic position of the studied samples, this estimate is in good agreement with the U-Pb age (543.9 ± 0.2 Ma [7]) of volcanogenic zircon from the middle part of the Nemakit-Daldynian Stage in the Olenek Uplift in northern Siberia and the U-Pb age (<555.3 Ma [9]) of the upper Vendian units in the White Sea region that contains the Ediacarian *Cyclomedusa plana*.

The initial $^{87}Sr/^{86}Sr$ ratio in fractions L2-L6 of limestones from Member III is within a range of 0.70829-0.70844 (table) and characterizes the sedimentation environment of the Ust'-Yudoma carbonate sequence. The above values fit the $^{87}Sr/^{86}Sr$ variation interval determined for other Upper Vendian-Ediacaran carbonate rocks (Fig. 3), such as the Nama Group in Namibia (543-549 Ma [11]), the Huqf Supergroup in Oman (544-554 (562) Ma [12]), the supratillite portion of the Windermere Supergroup in northern Canada [13], and the Tinnaya Formation in southern Siberia [10]. All these values demonstrate a substantial increase in the $^{87}Sr/^{86}Sr$ ratio in the Late Vendian ocean (0.7080-0.7085) relative to the Early Vendian basin (0.7067-0.7073 [11]). This increase was caused by the development of Pan-African orogeny as a sequence of geodynamic and tectonothermal events that promoted the accretion of major continental blocks of western and eastern Gondwana about 600 Ma ago [14, 15]. Ancient crustal rocks were exhumed to the surface by the accretionary and collisional orogens and eroded, supplying the radiogenic ^{87}Sr to the Vendian ocean.

Thus, we have obtained the first methodically reliable Pb-Pb isochron age, which is consistent with the stratigraphic position of the Ust'-Yudoma Formation, for UpperYudomian carbonate rocks in eastern Siberia. We also determined in the carbonates the initial ^{87}Sr/^{86}Sr ratio that characterizes the Sr isotopic composition of the Late Vendian ocean.

ACKNOWLEDGMENTS

We thank B.M. Gorokhovskii, N.N. Mel'nikov, and E.P. Kutyavin for assistance in the mass-spectrometric measurements.

This work was carried out in the framework of fundamental studies sponsored by the Division of Earth Sciences, Russian Academy of Sciences (programs "Problems of Origin and Evolution of the Earth's Biosphere" and "Isotope Geology: Geochronology and Material Sources." It was also supported by the Russian Foundation for Basic Research (project nos. 00-05-72011, 02-05-64333, and 02-05-65241) and Commission for Youth Affairs of the Russian Academy of Sciences (project no. 301).

REFERENCES

I. Semikhatov, M.A., Komar, V.A., and Serebryakov, S.N., *Yudomskii kompleks stratotipicheskoi mestnosti* (The Yudoma Complex in the Slratotype Locality), Moscow: Nauka, 1970.
2. Khomentovskii, V.V. and Karlova, G.A., *GeoL Geofiz.*, 1994, vol. 35, no. 10, pp. 3-13.
3. Khomentovskii, V.V. and Karlova, G.A., *Stratigr. Geol. Korrelyatsiya*, 2002, vol. 10, no. 3, pp. 13-34.
4. Zhuravleva, Z.A. and Komar, V.A., *Dokl. Akad. Nauk SSSR*, 1962, vol. 144, no. I, pp. 197-200.
5. Keller, B.M. and Semikhatov, M.A., *The Vendian System*, vol. 2: Regional Geology, Berlin: Springer, 1990.
6. Semikhatov, M.A., Gorokhov, I.M., Ivanovskaya, T.A., *et al*, *LitoL Polezn. Iskop.*, 1987, no. 5, pp. 78-96.
7. Bowring, S.A., Grotzinger, J.P., Isachsen, C.E., *et al.*, *Science*, 1993, vol. 261, no. 5126, pp. 1293-1298.
8. Ovchinnikova, G.V., Semikhatov, M.A., Vasil'eva, I.M., *et al.*, *Stratigr. Geol. Korrelyatsiya*, 2001, vol. 9, no. 6, pp. 3-16.
9. Martin, M.W., Grazhdankin, D.V., Bowring, S.A., *et al.*, *Science*, 2000, vol. 288, no. 5467, pp. 841-845.
10. Gorokhov, I.M., Semikhatov, M.A., Baskakov, A.V., *et al.*, *Stratigr. Geol. Korrelyatsiya*, 1995, vol. 3, no. I, pp. 3-33.
11. Kaufman, AJ., Jacobsen, S.B., and Knoll, A.H., *Earth Planet. ScL Lett.*, 1993, vol. 120, no. 3, pp. 409-430.
12. Burns, S.T., Haudenschild, U., and Matter, A., *Chem. Geol.*, 1994, vol. 111, no. 1/4, pp. 269-282.
13. James, N.R, Narbonne, G.M., and Kyser, T.K., *Can. J. Earth Sci.*, 2001, vol. 38, no. 12, pp. 1229-1262.
14. Trompette, R., *Precambr. Res.*, 1997, vol. 82, no. 1/2, pp. 101-112.
15. Meert, J.G., *Tectonophysics*, 2003, vol. 362, no. 1/4, pp. 1-40.